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Estimation of Light Intercepting Performance of Plant Canopy using Mean Leaf Area Weighted with Relative Light Intensity

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This study was conducted to estimate the light intercepting performance of plant canopy using mean leaf area weighted with relative light intensity which was regarded as efficient leaf area (L_e). The L,, the proportion of light intercepted in canopy to total light (R) and the amount of light received by L_e [I, $(=L_e \cdot R)$] were obtained from light attenuation formula. Thus,

$$L_e=\frac{1}{K}\cdot\left[1-\frac{KL}{\exp(KL)-1}\right] \qquad R=100\cdot\left[1-\frac{1}{\exp(KL)}\right] \qquad I_e=\frac{KL+1}{K}\cdot\left[1-\frac{}{\exp(KL)}\right]$$

where L=canopy leaf area index, K=light extinction coefficient, 100=relative light intensity above the canopy.

The calculation was done for [L,, L_e/L, R, I_e] when L=[0.5, 1, 2, 3, 4, 5, 6, 7, 8] and K=[0.3, 0.8, 1.3], resulting in the construction of 27 model canopies in the combination of L and K. The results obtained were as follows.

1. The L_e was increased with the rise in L and with the decrease in K.
2. The L_e/L declined as L and K increased.
3. The R was increased with the rise in L and K.
4. The I_e was increased with the rise in L, but the effect of K on I, was intricate when L was below 4.

The results l-4 showed that (1) with the canopy having very low leaf area index a large extinction coefficient allowed the canopy to intercept more amount of solar radiation, but (2) when the canopy leaf area index was high a small extinction coefficient enabled the canopy to have larger efficient leaf area that could receive larger amount of sunlight.

It was suggested that efficient leaf area might be an index available to the analysis of the relationship between canopy structure and light interception, and larger efficient leaf area might be obtained by having leaves inclined more vertically.

INTRODUCTION

Forages are a major source of feed to ruminant animals (Mahadevan, 1982). The production from ruminants depends on the quality as feed (Van Soest, 1982 ; Minson, 1990) and on the dry matter production (Simpson and Culvenor, 1987 ; Humphreys, 1991a, 1991b) of forages.

The productivity of forages is controlled by the amount of solar radiation intercepted in plant canopy, provided all the other factors do not limit the growth of plants (Gardner et al., 1985 ; Charles-Edwards et *al.,* 1986 ; Simpson and Culvenor, 1987 ; Sheehy and Johnson, 1988 ; Humphreys, 1991a, 1991b). The interception of light by

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canopy leaves is described using light attenuation formula (Monsi und Saeki, 1953 ; Saeki, 1960). Monteith (1965) also presented a similar formula to study the light distribution in canopy.

Between the top and the bottom layers of leaves there is a shading of lower leaves by upper leaves, and this is mainly affected by the area and inclination of leaves. Therefore, useful indices are needed to estimate how efficiently the canopy leaf area is involved in light receiving.

This study was designed to estimate the light intercepting performance of plant canopy, using efficient leaf area indicating mean leaf area weighted with relative light intensity and the amount of light received by efficient leaf area.

LIGHT INTERCEPTING PERFORMANCE OF CANOPY

Light interception by canopy leaves

The light interception by canopy leaves is described using the following formula for light attenuation (Monsi und Saeki, 1953),

$$I_j = 100 \cdot \exp(-KF_j) \tag{1}$$

where F_j=cumulative leaf area index from the top to the jth layer of leaves, 100= relative light intensity above the canopy, I_j=relative light intensity below the jth layer of leaves, K=light extinction coefficient of the canopy.

Description of efficient leaf area and amount of light received

1. Efficient leaf area of canopy

In this study mean leaf area weighted with relative light intensity is regarded as efficient leaf area (L,).
Thus,

$$L_e = \int_0^L F \cdot [100 \cdot \exp(-KF)]dF \Big/ \int_0^L 100 \cdot \exp(-KF)dF$$
$$= \frac{1}{K} \cdot \left[1 - \frac{KL}{\exp(KL)-1}\right] \tag{2}$$

where L=canopy leaf area index, K=light extinction coefficient.
The L_e approaches l/K with the rise in L and K.

Then, the ratio of L_e to L,

$$\frac{L_e}{L} = \frac{1}{KL} \cdot \left[1 - \frac{KL}{\exp(KL)-1}\right] \tag{3}$$

estimates the proportion of efficient leaf area to canopy leaf area index. As L and K increase there occurs the approach of L_e/L towards $1/(KL)$.

2. Amount of light received by efficient leaf area

The proportion of light received in canopy to total light (R) is expressed as follows,

$$R=100\cdot\left[1-\frac{1}{\exp(KL)}\right] \tag{4}$$

where L=canopy leaf area index, K=light extinction coefficient.
With the rise in L and K the R approaches 100.
Assuming that R is intercepted by L_e, the amount of light received by efficient leaf area (I_e) is as follows,

$$\begin{aligned} I_e &= L_e\cdot R \\ &= \frac{100}{K}\cdot\left[1-\frac{KL+1}{\exp(KL)}\right] \end{aligned} \tag{5}$$

The I_e approaches $100/K$ with the increase in L and K.

Calculation of [L_e, L_e/L, R, I_e] and considerations for I_e as affected by L_e and R

The calculation was done for four indices, namely [L,, L_e/L, R, I_e] when L=[0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0] and K=[0.3, 0.8, 1.3]. This constructed 27 model canopies in the combination of canopy leaf area index (L) and light extinction coefficient (K).

1. [L_e, L_e/L] and [R]

The L_e is increased with the rise in L and with the decrease in K, but the rate of rise in L_e is reduced as L increases (Table la, Fig. 1). The difference in L_e between a canopy with smaller K and that with larger K becomes larger with the increase in L. Therefore, when K is larger there is the approach of L_e towards l/K with lower L. These results show that the canopy has a larger efficient leaf area when the extinction coefficient is smaller, and this is more effective when the canopy has a higher leaf area index.

The L_e/L declines when there is an increase in L and K (Table lb, Fig. 2). The difference in L_e/L between a canopy with smaller K and that with larger K becomes larger as L increases. Therefore, the L_e/L approaches $1/(KL)$ with lower L when K is larger. These results show that the proportion of efficient leaf area is larger when the canopy has a smaller extinction coefficient, and this is more effective when the canopy has a higher leaf area index.

The R is increased with the rise in L and K, but the rate of rise in R is reduced as L increases (Table 2a, Fig. 3). The difference in R between a canopy with larger K and that with smaller K becomes smaller with the increase in L. Therefore, when K is larger there is the approach of R towards 100 with lower L. These results show that the proportion of intercepted light is larger when the canopy has a larger extinction coefficient, but this is more effective when the canopy has a lower leaf area index.

2. Considerations for I_e as affected by L_e and R

The I_e is expressed by the product of L_e and R, and I_e is increased as L rises (Table 2b, Fig. 4). However, the effect of K on I, is intricate when L is between 0.5 and 4. When L is 0.5, the canopy has a larger I_e when K is 1.3 than when K is smaller. This is caused by the larger R because there are little differences in L,. When L is 2, the I_e of the canopy showing 0.8 for K becomes slightly larger than that of the

Table 1. Efficient leaf area of canopy (L_e) and the proportion of efficient leaf area to canopy leaf area index (L_e/L) in 27 model canopies.

a) L_e

		Light extinction coefficient (K)		
		0.3	0.8	1.3
Canopy leaf area index (L)	0.5	0.244	0.233	0.223
	1.0	0.475	0.434	0.395
	2.0	0.901	0.744	0.609
	3.0	1.278	0.951	0.707
	4.0	1.609	1.080	0.747
	5.0	1.897	1.157	0.762
	6.0	2.145	1.200	0.767
	7.0	2.357	1.224	0.768
	8.0	2.535	1.237	0.769

b) L_e/L

		Light extinction coefficient (K)		
		0.3	0.8	1.3
Canopy leaf area index (L)	0.5	0.488	0.467	0.446
	1.0	0.475	0.434	0.395
	2.0	0.450	0.372	0.304
	3.0	0.426	0.317	0.236
	4.0	0.402	0.270	0.187
	5.0	0.379	0.231	0.152
	6.0	0.358	0.200	0.128
	7.0	0.337	0.175	0.110
	8.0	0.317	0.155	0.096

canopy in which K is 1.3. This is due to the larger L_e which offsets the smaller R. When L has increased up to 4, the canopy where K is 0.3 shows larger I_e than that of canopies having larger K. This is caused by the larger L_e which more than makes up for the smaller R. The I_e approaches $100/K$ with lower L when K is larger. These results are accounted for as follows.

Canopies with very low leaf area index show similar efficient leaf area even when there are large differences in light extinction coefficient. Therefore, a large extinction coefficient allows the canopy to intercept more amount of solar radiation. However, when the canopy leaf area index is high, a small extinction coefficient enables the canopy to have larger efficient leaf area that can receive larger amount of sunlight. These results may be associated with some theoretical works (Saeki, 1960 ; Kubota et *al.*, 1971 ; Loomis and Williams (1969) as quoted by Gardner *et al.*, 1985) in which it is shown that the photosynthetic activity with small extinction coefficient is lower when the canopy leaf area index is low, but becomes higher when having high leaf area index, compared with that obtained by large extinction coefficient. When estimating the photosynthetic characteristic of canopy, it is recommended to use the efficient leaf area obtained, in equation (2), by integrating F from 0 to the cumulative leaf area index associated with the receiving of radiation above the light compensation

Table 2. The proportion of light intercepted in canopy to total light (R) and the amount of light received by efficient leaf area (I_e) in 27 model canopies.

a) R

		Light extinction coefficient (K)		
		0.3	0.8	1.3
Canopy leaf area index (L)	0.5	13.929	32.968	47.795
	1.0	25.918	55.067	72.747
	2.0	45.119	79.810	92.573
	3.0	59.343	90.928	97.976
	4.0	69.881	95.924	99.448
	5.0	77.687	98.168	99.850
	6.0	83.470	99.177	99.959
	7.0	a7.754	99.630	99.989
	8.0	90.928	99.834	99.997

b) $I_e(=L_e \cdot R)$

		Light extinction coefficient (K)		
		0.3	0.8	1.3
Canopy leaf area index (L)	0.5	3.395	7.694	10.663
	1.0	12.312	23.901	28.706
	2.0	40.634	59.384	56.355
	3.0	75.839	86.445	69.293
	4.0	112.458	103.600	74.292
	5.0	147.392	113.553	76.056
	6.0	179.054	119.033	76.646
	7.0	206.795	121.949	76.836
	8.0	230.520	123.463	76.896

point.

With the growth of plants, light intercepting activity of canopy depends more on the increase in efficient leaf area. The larger increase in efficient leaf area is caused by the smaller extinction coefficient. This may be achieved, for instance, by having the leaves of more vertical inclination which allow the lower leaves to receive larger amount of light (Gardner et *al.,* 1985). The amount of light received by efficient leaf area approaches $100/K$ as plants grow, due to the approach of efficient leaf area towards $1/K$ and of the proportion of light intercepted in canopy towards 100. This approach occurs with lower leaf area index when extinction coefficient is larger.

An approximate value may be obtained for efficient leaf area without determining the light extinction coefficient, provided leaf area and relative light intensity are measured for each layer of canopy using a stratified clip method. This is obtained by the following calculation,

$$\text{Approximated} \quad L_e = \left(\sum_{j=1}^{n} F_j \cdot I_j\right) \Big/ \left(\sum_{j=1}^{n} I_j\right) \tag{6}$$

where F_j=cumulative leaf area index from the top to the jth layer of leaves, I_j=

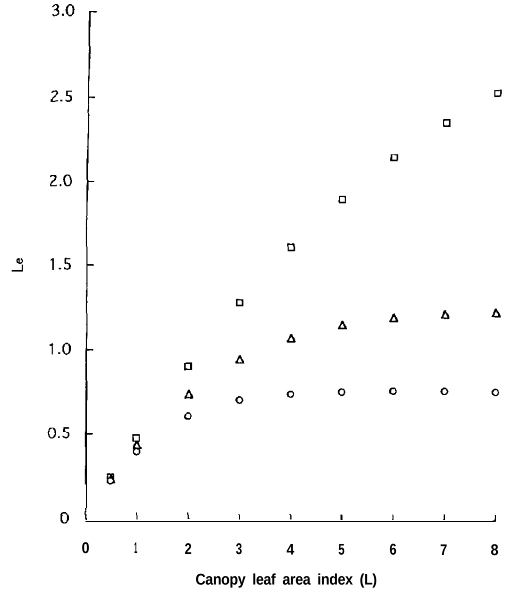

Fig. 1. Efficient leaf area of canopy (L_e) in 27 model canopies [K=0.3 (□), 0.8 (△), 1.3 (○)].

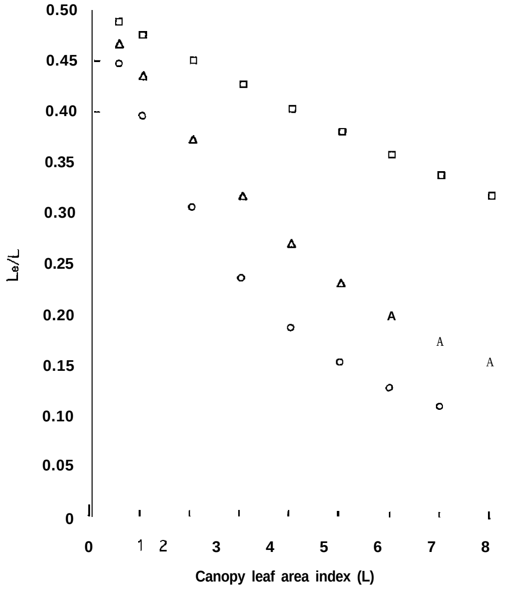

Fig. 2. The proportion of efficient leaf area (L_e) to canopy leaf are index (L) in 27 model canopies [K=0.3 (□), 0.8 (△), 1.3 (○)].

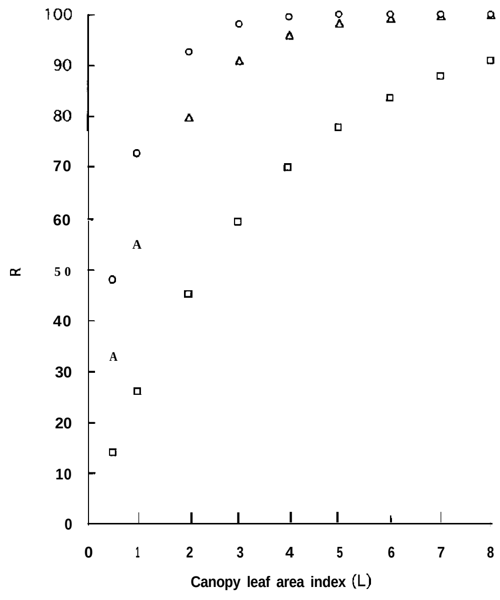

Fig. 3. The proportion of light intercepted in canopy to total light (R) in 27 model canopies [K=0.3(□), 0.8 (△), 1.3 (○)].

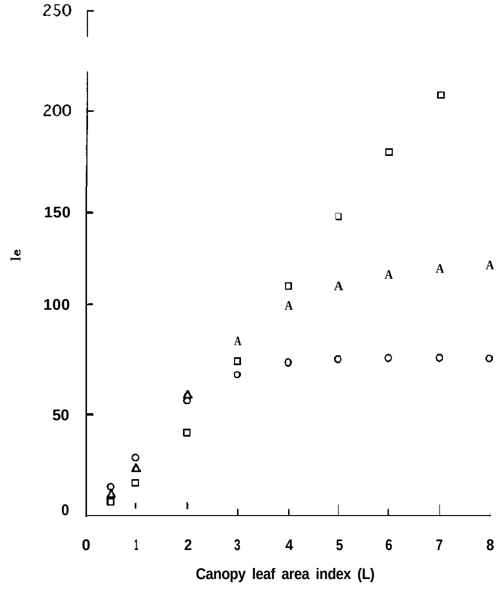

Fig. 4. The amount of light received by efficient leaf area of canopy {$I_e(=L_e \cdot R)$} in 27 model canopies [K=0.3 (□), 0.8 (△), 1.3 (○)].

relative light intensity below the jth layer of leaves, n=the number of layers. In actual canopies the extinction coefficient at upper layer is often different from that at lower layer, and this is mainly due to the difference in leaf inclination between them. Therefore, the proximate efficient leaf area is expected to be an index available to the investigation of light receiving in canopy when the light extinction coefficient is considered difficult to be actually simplified.

It is suggested from this study that efficient leaf area may be an index available to the analysis of the relationship between canopy structure and light interception, and larger efficient leaf area may be obtained by having leaves inclined more vertically.

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